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Review on Structure-based Errors of Parallel Kinematic Machines in Comparison with Traditional NC Machines

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Abstract. Machining technology is developed with increasing flexibility to adapt to the rapid changes of the market. Parallel kinematic machines (PKMs) have demonstrated great flexibility to suit the demands, but it is still not possible to achieve as high accuracy as the traditional NC machines (TNCMs). This paper presents a general review on the structure-based errors of PKMs in comparison with TNCMs to reveal physical causes and the relevance to the final uncertainty. The geometric/kinematic, gravitational, and thermal aspects in both TNCMs and PKMs are identified as structure-based error sources. Errors in each aspect are comparatively analyzed between PKMs and TNCMs, and inherent differences are found to bring new challenges to the final uncertainty of PKMs. Finally, perspectives in each aspect are highlighted for accuracy improvement of PKMs.

Keywords: Parallel kinematic machine, traditional NC machine, geometric/kinematic, gravitational, thermal, error.

1 Introduction

Machining technology is developed with increasing flexibility in order to adapt to the changes (e.g., short lead-time, more variants, low and fluctuating volumes, low price) taking place in the market [1–3]. The effective use of robot machine tools has proved critical towards that direction [2–6]. A parallel kinematic machine (PKM), also known as parallel robot exhibits its superior dynamic performance to achieve quality, reliability, and productivity demands while possessing great flexibility, which will be the key technology in future 'plug and play' machining systems [7]. After first PKM publicly presented on the IMTS fair in 1994, commercialized PKMs have been adopted in industrial application [3, 7]. Up to now, PKMs (e.g., Exechon [8], Tricept [9], Z3 [10] and A3 [11] Sprint Head) have demonstrated great flexibility and relatively improved precision capability for the machining of large parts, such as milling and drilling aero-structures [6, 12, 13].

However, the development and implementation of parallel theoretical capabilities into the PKMs are rather in infancy compared to the long experience of traditional NC machines (TNCMs), which have an open-loop serial kinematic chain. That highlights the double-edged sword effects of applying parallel structure. Although PKMs theoretically should gain high accuracy due to its closed-loop kinematic chain resulting in few error accumulating effects, it also introduces new problems, such as the coupled errors (e.g., a single axis error will cause sources in all DOF of the end-effector) [14] which still cannot be well controlled. Specific accuracy comparisons between PKMs and TNCMs could be found in reference [7, 14–17] under certain levels, which have proved that there are still great barriers to achieve as high accuracy as TNCMs with PKMs, and deviations of PKMs could be induced by vast of reasons.

As we know, machining, specifically in subtractive one, is the removal of material from a clamped workpiece, by using specific cutting tool and parameters on a certain machine tool, whether a PKM or a TNCM, to obtain the component with desired profiles. Machine tool, cutting tool, processing method and clamping system as shown in Fig. 1 are the basic elements to perform the machining on a raw material to obtain a machined component. However, the machined component is not always in accordance with the requirements on dimensional and geometrical accuracy. It is because that each of the basic elements will induce deviations in the actual cutting positions from the theoretical values, defined as errors. The high accuracy component could only be achieved beyond the error effects of each element in Fig. 1 and that is what high precision machining pursues. Therefore, significant differences of structure, movability, control, etc. between PKMs or TNCMs definitely contribute to distinguishing errors within the four elements.

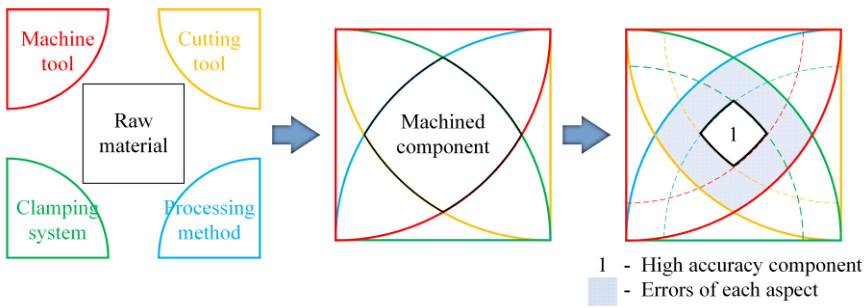


Fig. 1 Subtractive machining process to obtain high accuracy component

To improve the accuracy of PKMs, the first step and key factor are to identify the error sources within the four elements and to reveal the physical causes and the relevance to the final uncertainty. PKMs are unique for their structures, and structured-based error source should be one of the most influential factors on their final accuracy. Restricted by the article length, the focus of this review is only to address structured-based errors, and to emphasize their inherent difference in comparison with TNCMs, to provide a perspective view of challenges.

2 Structure-based Error Sources

Structure-based errors here refer to the static and quasi-static errors from the structures itself as well as moving components such as slide, joint, etc. Tracing the sources of these errors, they generally include geometric/kinematic, gravitational, and thermal aspects. The physical causes of these three aspects have been deeply investigated in TNCMs [7, 18–24].

i. Geometric errors are basically derived from design, manufacturing and assembly of the machine tool and its components, such as the misalignments of axes, slideways degradation or other guide imperfection issues induced by the mechanical imperfections. These errors are stable or changing slowly over time e.g. due to foundation drifts, wear or material aging. Kinematic errors are concerned with the motion errors induced by the components. The boundary to define an error as geometric or kinematic is diffuse.

ii. Since no object is perfectly rigid, the gravity of the structural components in any machine tool will cause some deflections. The combined deflections of all the components consequently form the finial gravity-induced errors, and they are generally dependent on the real-time pose (i.e., position and orientation) during the actual machining process.

iii. Causes of thermal errors are more complicated. That includes the thermal expansion of guideways heated by the ball screw drives, the expansion of the frame heated or cooled by the machine tool itself or external heat sources (e.g., environment), etc. In addition, most heat sources are time-dependent and at universal/local workspace levels, which make non-uniform temperature distributions and rather difficult to control.

3 Structure-based Errors Comparisons

TNCMs generally consist of the bed, column, spindle and various linear and/or rotary axes, and that is no exception for PKMs. These two kinds of machine tools almost share the same error sources as well as their causes. However, the more complex the structure and constraints, the more errors and difficulties to calibrate. PKMs are quite complex in the structure such as the non-orthogonal driven legs and contain far more constraints than TNCMs. Error sources of PKMs exhibit some new features.

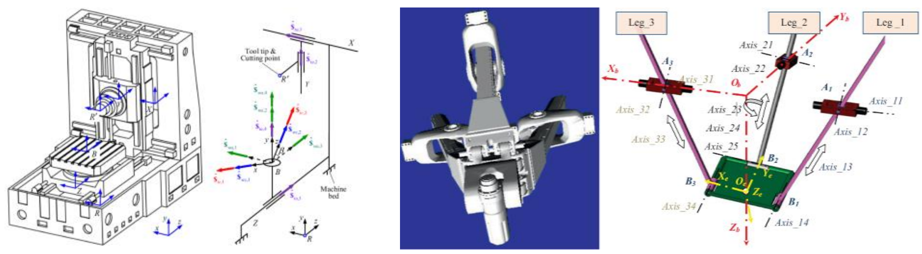
3.1 Geometric/kinematic Errors

When designing machine tools, the geometric error of each component is always a significant factor to be considered [25]. Actually, each component of machine tools has independent geometric errors, and what is critical between PKMs and TNCMs lies on how the errors are accumulated to affect the final position of the tool endpoint and how to calibrate its accuracy. Errors from components or from the assembly (e.g., axis misalignment) will fundamentally affect the accuracy through the kinematic chain transmissions. For TNCMs, abundant studies have revealed that errors could be added step-by-step through the open-loop kinematic chains as illustrated in Fig. 2(a), and consequently, the corresponding calibration and compensation could be implemented to minimize geometric errors [19, 20, 26]. Comparatively, PKMs have a closed-loop kinematic chain always with non-orthogonal legs, see Fig. 1(b), and their kinematic relationships are considerably complex. The final errors induced by geometric errors of components can't be simply added up, and the evaluation of the geometric errors effects mainly facing two aspects of difficulties.

i. Typically, the kinematic model of a PKM is established neglecting the geometric errors. However, geometric errors (e.g., parallelism errors of two theoretically parallel legs) sometimes are under high constraints and will even lead to great uncertainty to the normal PKM kinematic model [27], which makes the normal model unsuitable for calibration and control of the PKM precisely in actual motion.

ii. Much more geometric parameters are needed to calibrate PKMs than TNCMs [28] which definitely leads to heavy computational burden if following each step of the closed-loop kinematic chain. More importantly, the accurate identification of calibration required geometrical parameters is the key to accurate positioning capability for PKMs [24], but not all the calibration required data could be obtained exactly.

Up to now, popular methods of reducing PKM geometric/kinematic errors are applying the generally simplified reverse kinematic model and limited numbers of calibration poses to averagely complete the whole workspace calibration [29]. To further minimize these errors, constraint errors should be first checked and measured independently, before determining the reverse simplified kinematic model, to establish a better calibration base. Certainly, the more measuring poses are applied, more accuracy the PKMs will be achieved in the whole workspace.



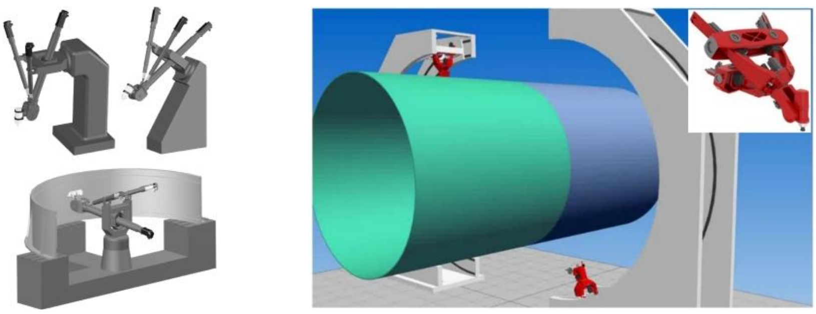
(a) (b)

Fig. 1 Schematic diagram of machine tools (a) 4-axis TNCM [18], (b) Exechon PKM [30]

3.2 Gravity-induced Errors

The gravity-induced errors exhibit more interesting and distinct features between TNCMs and PKMs. TNCMs always have the relatively fixed structure resulting in the approximately constant gravity-induced errors in the whole workspace, which could be easily compensated by current calibration methods [31]. In contrast, the gravity of a PKM will significantly change due to that the slides protrude significantly different lengths for the end-effector reaching within a large range especially like at a singular point, near an edge of the workspace or under a large tilt angle. This leads to the remarkable non-consistent stiffness of a PKM as well as gravitational effects at different poses, and consequently, the gravity-induced errors are highly pose-dependent. Therefore, the stiffness mapping considering gravitational effects [32] and specific gravity-effect modeling [33] have been investigated and effective reductions of gravity-induced errors are achieved.

In addition, in the development of future flexibility machining system, reconfigurable position and orientation concepts are proposed and put into practice in both TNCMs [34, 35] and PKMs [36–38], and the gravity-induced errors are particularly highlighted in PKMs. Due to the great advantages (e.g., high payload-to-weight ratio) of reconfigurable tooling, the PKM has been recognized as a standard module to extend workspace to a more universal space as shown in Figures 3(a) and 3(b). The gravity effects on PKMs face flexible change especially in machining large components like the fuselage in Fig. 3(b). Meanwhile, some up-to-date walking PKMs [39, 40] are developed to contribute more flexibility to the machining process, and their operating positions also affect the gravity-induced errors. Therefore, the reconfigurability brings the PKMs great challenge of the complex gravitational effects on the machining accuracy, but the relevant studies are still in infancy. Gravity-induced errors due to reconfigurability, as well as the corresponding compensation strategies, need to be further investigated.



(a) (b)

Fig. 3 Reconfigurable PKMs (a) TriVariant [41], (b) Exechon [42]

3.3 Thermal Errors

Although the thermal error sources in TNCMs and PKMs are similar, the error effects feature differently. Thermal errors in TNCMs are independent on each component, and their combined effects could also be added up for the open-loop structure, but the non-uniform temperature distributions make it difficult to predict and compensate in Fig. 4(a). For PKMs, the thermal effects of the legs induced by screw drives are the major thermal error source [24], and the parallel structure makes the legs always perform asymmetry movement simultaneously resulting unequal temperature elevations [5]. Meanwhile, the thermal effects such as actual thermal defection of legs and frame are not independent and will be affected by each other within the closed-loop structure in Fig. 4(b). Thus, both of these make the PKM more susceptible to thermal loads, even besides the non-uniform temperature distributions. Although some studies in thermal error modeling [43], compensation [40] and cooling structure components [19, 35] have been conducted to decrease thermal errors of PKMs, it is far beyond the high accuracy expectation even compared with TNCMs. And co-thermal effects within the closed-loop structure could be attractive aspects in increasing the accuracy.

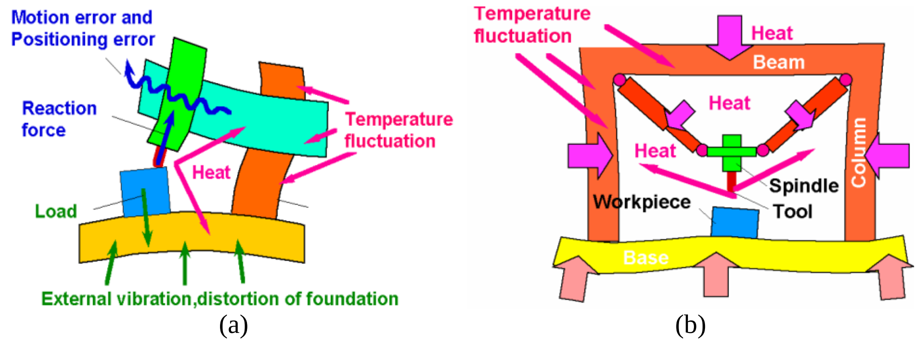


Fig. 2 Thermal expansion machine tools (a) TNCMs [44], (b) PKMs [45]

4 Conclusion

In this paper, structure-based error sources of both TNCMs and PKMs are identified in geometric/kinematic, gravitational, and thermal aspects. These structure-based errors in each aspect are comparatively analyzed between TNCMs and PKMs, and inherent differences show that the structure complexity, the close-loop chains as well as the reconfigurability of PKMs bring new challenges to the final uncertainty of PKMs. Modified kinematic model with constraint errors, gravity-induced errors due to reconfigurability, and co-thermal effects within the closed-loop structure are highlighted for further investigations on improving the accuracy of PKMs. Also, the machining errors in PKMs induced by the other three basic elements i.e., cutting tool, processing method and clamping system will be reviewed in the future.

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